

Radiometric Spacecraft Tracking for Deep Space Navigation

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BIOGRAPHY

Gabor Lanyi received the Ph.D. degree in physics from Syracuse University in 1977. He has been with the Jet Propulsion Laboratory since 1979 working primarily in the area of astrometry for deep space tracking application. His research interest also includes refraction effects in terrestrial media, GPS based ionospheric content determination, weak signal detection, and fundamental aspects of physics.

James Border received the B.A. in physics from the University of Iowa, Iowa City, in 1974 and the Ph.D. degree in mathematics from the University of California, San Diego, in 1979. He has been with the Jet Propulsion Laboratory since 1981 working on development of radiometric tracking systems for deep space and near Earth missions

ABSTRACT

Interplanetary spacecraft navigation relies on three types of terrestrial tracking observables. 1) Ranging measures the distance between the observing site and the probe. 2) The line-of-sight velocity of the probe is inferred from Doppler-shift by measuring the frequency shift of the received signal with respect to the unshifted frequency. 3) Differential angular coordinates of the probe with respect to natural radio sources are nominally obtained via a differential delay technique of Δ DOR (Delta Differential One-way Ranging). The accuracy of spacecraft coordinate determination depends on the measurement uncertainties associated with each of these three techniques. We evaluate the corresponding sources of error and present a detailed error budget

RADIOMETRIC OBSERVABLES

The telemetry link between a spacecraft and the terrestrial observing stations must contain sufficient signal structure for various measurements to reconstruct the spacecraft

trajectory. Three types of observables are nominally measured: 1) line-of-sight delay resulting in distance d , (range); 2) the frequency shift of the received signal due to the motion of spacecraft relative to the receiving station, resulting line-of-sight velocity \dot{d} ; 3) differential delays between two receiving stations for the spacecraft signal and an angularly nearby natural reference source-signal, resulting in the differential angle θ . A typical observation scenario is depicted in Fig. 1 [1].

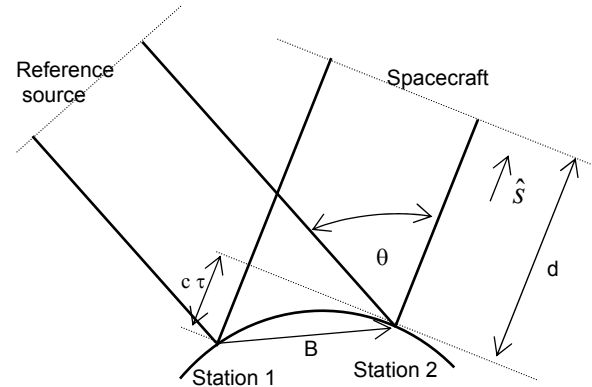


Fig. 1. Terrestrial observation of a distant spacecraft and a reference source with two receiving stations. The distance between a terrestrial receiver and a radio source is denoted by d . The symbol θ denotes the angular separation between the line of sight of the spacecraft and the reference radio source, and τ represents the delay between the signal arrival times at the two receivers. The dotted lines represent the instantaneous signal wave front at emission and receiving times. The symbol B represents the baseline vector between the two receiver sites and \hat{s} is the unit vector pointing to the radio source (this figure is a replica of Fig. 1 of [1]).

Sequential determination of combined range, line-of-sight velocity and the angular position of the spacecraft allows for proper trajectory corrections leading to sufficiently accurate target entry coordinates of the spacecraft for certain classes of mission [2],[3]. Targets with large ephemeris-uncertainty requires also on-board guidance.

Currently, 1--2 nanoradian (nrad) angular position accuracy achieved for probes targeting Mars [4],[5]. Subsequently, we will exhibit the distribution of error sources leading to such an accuracy level.

SOURCES OF SPACECRAFT POSITION ERRORS

In the following we will exhibit the contributions of various error sources to the three type of measurements described above for the Deep Space Network (DSN) of NASA [6]. Only a brief exposition of error budget is given, the origin of the actual error values is not within the scope of this paper. There are three basic sources of deterministic and random errors, in occurrence order of signal propagation from the spacecraft: 1) spacecraft-signal and reference-source-position uncertainties; 2) terrestrial and solar media induced delays; 3) ground receiver instrumental, positional and timing uncertainties. These errors will affect in various ways the range (distance), Doppler-shift (line-of-sight velocity) and Δ DOR (angle) measurements.

The spacecraft position is determined with a least-squares estimation orbital determination (ODP) computer program applying the models described in [3]. The nominal daily observational period is about 8 hours, though the frequency and duration of position estimates may depend on the type of mission and its temporal state. The errors described below are used by the ODP for either weighting the observables or a priori parameterization. The range and Δ DOR errors given below refer to a 600-s duration. The range measurements are repeated during the observing period, but Δ DOR is essentially a single observation. On the other hand, the Doppler-shift errors given refer to a DSN traditional 60-s sampling interval repeated in a continuous sequence.

Δ DOR is essentially a doubly differenced delay measurement on angularly nearby radio sources. Therefore, the common terrestrial-platform errors and the common delay errors in the signal paths of the spacecraft and the reference-source are significantly reduced resulting in high differential angular accuracy. This feature of Δ DOR can be significant, in particular in the perpendicular direction to the ecliptic plane, where the ranging and Doppler-shift measurement accuracies are lower. Figure 2 illustrates the range error scenario for a single range measurement. The error in the target plane is reduced by triangulation involving sequences of measurements at multiple sites.

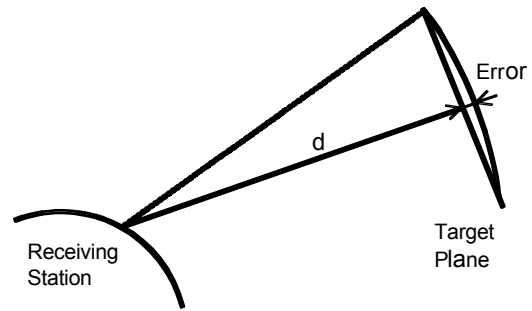


Fig. 2. Propagation of range error into angular error for a single range measurement. At Mars, a one meter range error results in kilometer-level errors on the target plane. In the direction of the intersection between the target and ecliptic plane, the error is reduced by multiple observations on the rotating Earth. However, in the perpendicular direction to the above intersection, there is a smaller reduction in error.

RANGE

Fig. 3 lists the various sources of errors. The term systematic refers to the unmodeled part of non-random phenomena. The item Station-Delay is the delay-calibration error of the calibrated part of the receiver signal path. Correspondingly, the term Z-Correction is the

uncertainty in the estimation of an extra delay introduced by the calibration process minus the uncalibrated delay part of the signal path [7]. The *range* is currently the least accurate observable in trajectory determination.

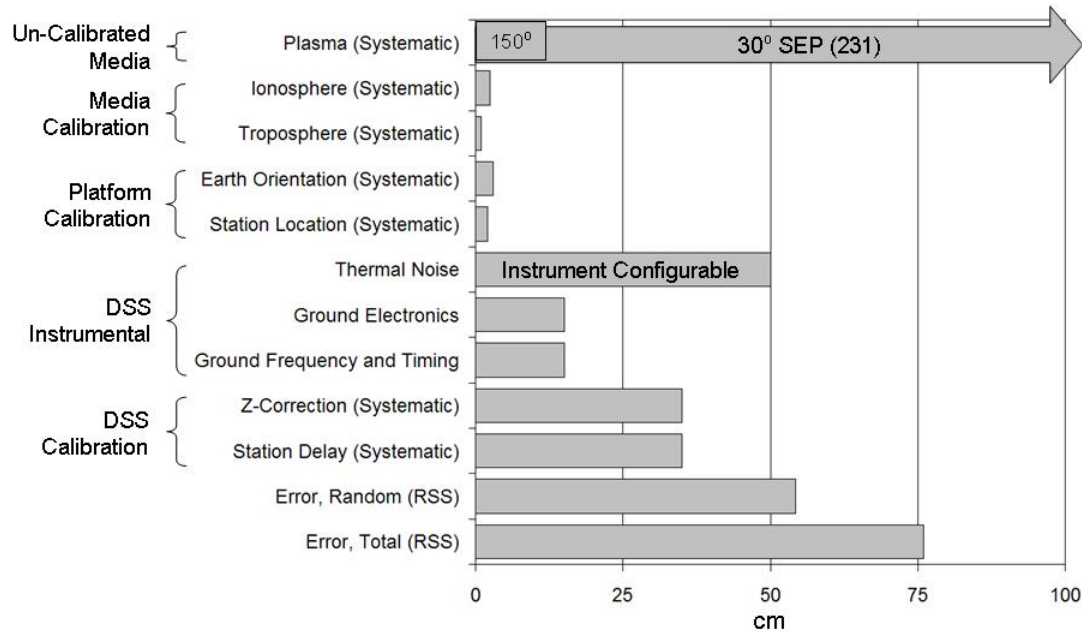


Fig. 3. DSN Range Error Distribution. The symbol SEP stands for the Sun-Earth-Probe angle.

DOPPLER-SHIFT

Fig. 4 lists the various sources of errors at the nominal DSN sample interval of 60 seconds. The Doppler-shift observational input to the ODP is sampled at the 60

second intervals and thus the a priori error given to the ODP at 60 s will contribute approximately to the daily estimates at the square-root of 60s/8h scaled level. The daily systematic media and terrestrial position related errors are included here as an equivalent Doppler-velocity observable error. This is performed by error propagation analysis via the particular physical model (with average physical parameters) after the appropriate conversion to rate and the above scaling.

The Doppler-shift observable is the most versatile observable in trajectory determination. In particular, its Earth-rotation induced periodicity provides valuable geometric information.

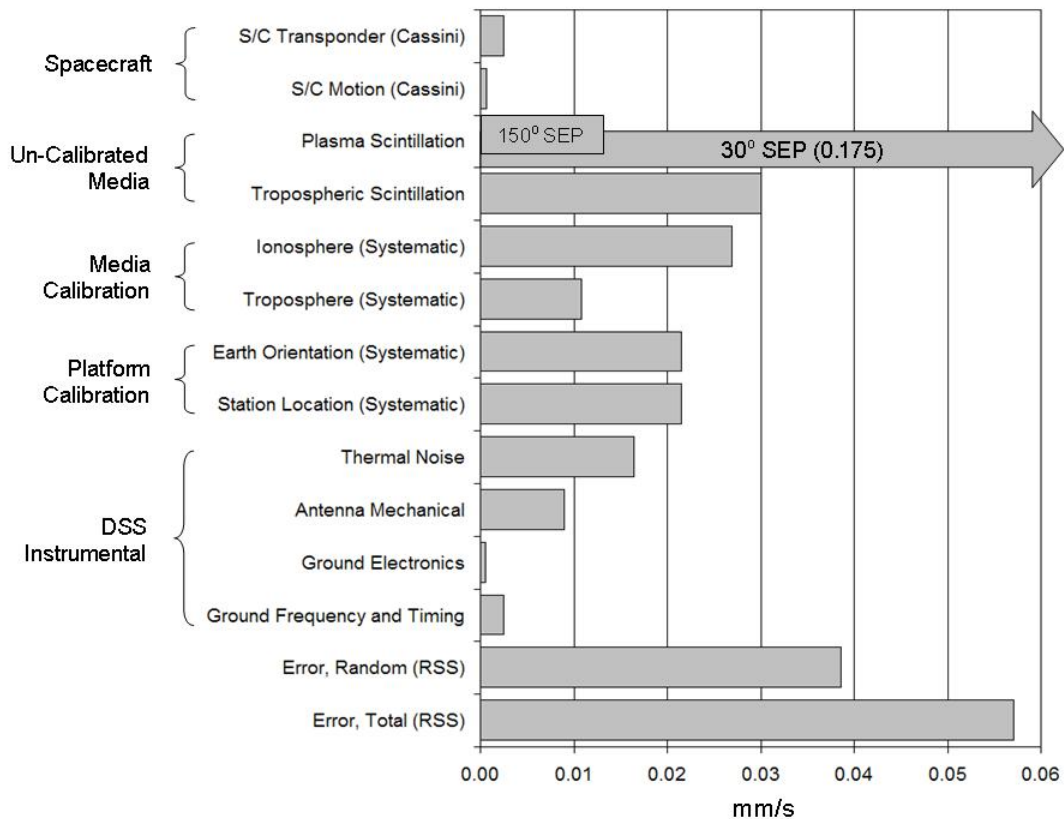


Fig. 4. DSN Doppler-velocity Error Distribution. The four systematic items represent Doppler-velocity equivalent error values on the 60 second integration scale..

Δ DOR

Fig. 5 lists the various sources of errors at integration interval of 600 seconds. The Δ DOR measurement is

performed essentially once per DSN baseline during the spacecraft diurnal observing period. Due to the need of mutual visibility from two DSN stations, Δ DOR measurements are carried out at a much lower temporal rate than the ranging and Doppler-shift measurements. Its high accuracy is particularly important before final trajectory correction for probe entry.

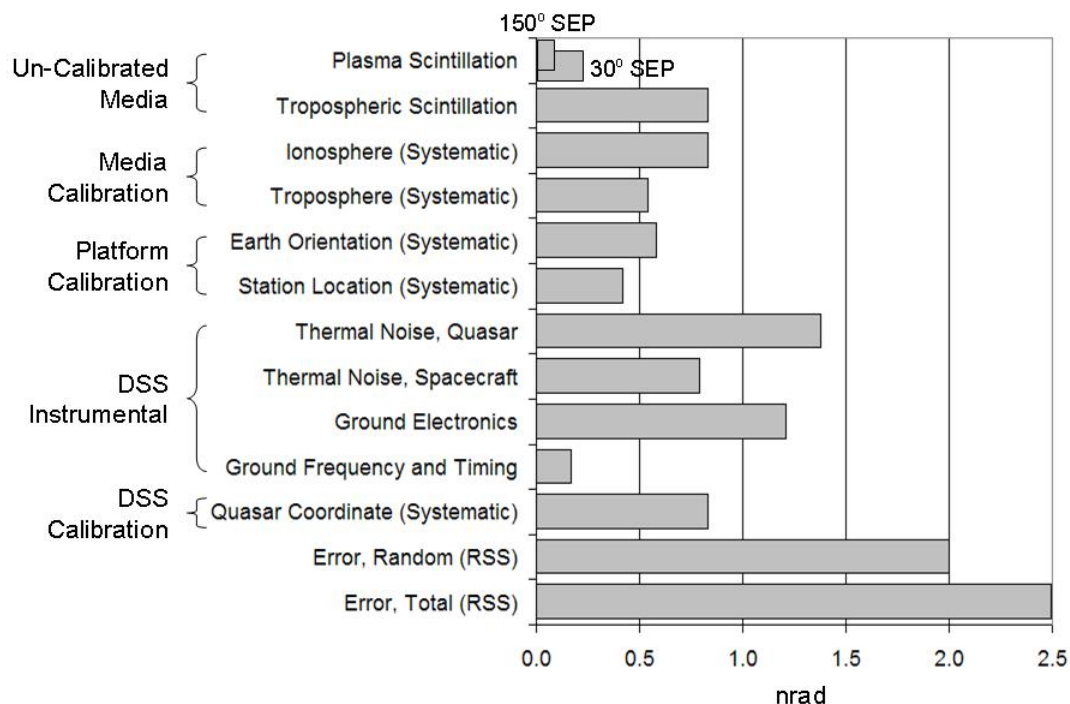


Fig. 5. DSN Δ DOR Error Distribution. Note the large relative reduction in plasma scintillation error in comparison to the other two observables.

ACKNOWLEDGMENTS

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